Development of deflection hardening geo-polymer based ductile fibre reinforced cementitious composites

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ABSTRACT:

Ductile fibre reinforced cementitious composites (DFRCC) is cement based composite reinforced with short random fibres (metallic and/or non-metallic) which exhibits deflection-hardening and multiple-cracking behaviours in bending. It is a special class of high performance fibre reinforced cementitious composite (HPFRCC) that has higher deflection capacity than that of regular fibre reinforced concrete (FRC). Current DFRCCs are limited to cement rich matrix system. This paper reports the development of geo-polymer based DFRCC where the cement binder in DFRCC is replaced by fly ash based geo-polymer binder where alkaline liquids (sodium hydroxide and sodium silicate) are used to activate the fly ash. In this study, three types of fibers are consider namely steel and two types of polyvinyl alcohol (PVA) fibers having different diameter, length and elastic modulus. The fiber used in the development of both cement based and geo-polymer based DFRCCs is limited to single fiber type. The effects of two different sand sizes (1.18mm, and 0.6mm) and sand/binder ratios of 0.5 and 0.75 on the deflection hardening and multiple cracking behaviour of both types of DFRCC are also evaluated. Results revel that the deflection hardening and multiple cracking behaviour can be achieved in geo-polymer based DFRCC similar to that of cement based system. For a given sand size and fiber and sand contents, comparable ultimate flexural strength and the deflection at peak load are observed in both cement and geo-polymer based composites. The proposed development exhibit a significant benefit for the use of geo-polymer based DFRCC over cement based system as the former one is ***green*** in terms of ***no cement use***.

1 INTRODUCTION

High performance fibre reinforced cementitious composites (HPFRCC) have been steadily developed in the last two decades. One of the salient features of HPFRCC is its strain hardening and multiple cracking behaviours in both tension and bending [1]. It is a short fibre (metallic and/or non-metallic) reinforced cement based composites where fibre content between 2% and 3% by volume appears to be the most attractive due to ease of processing. Great interest in this area is observed through the development of engineered cementitious composites (ECC) [2] and ductile fibre reinforced cementitious composites (DFRCC) [3]. Ductile fibre reinforced cementitious composites (DFRCC) is cement based composite reinforced with short random fibres which exhibits deflection-hardening and multiple-cracking behaviours in bending. It is a special class of HPFRCC that has higher deflection capacity than that of regular fibre reinforced concrete (FRC) and exhibit deflection hardening and multiple cracking behaviours. However, current version of DFRCC is limited to cement rich matrix, although the replacement of cement with fly ash is reported in few studies [4].

The need for environmentally friendly construction materials for sustainable development is an important issue in the present time. The concrete industry is said to be one of the significant contributors to global warming. This fact is due to the use of Portland cement as the main component in making concrete and cement based composites. The cement industry is responsible for about 6% of the CO_2 emission, which is the main cause of the global warming. However, the use of concrete and cement based composites as the most widely used construction materials are still unavoidable in the foreseeable future. In this respect, the efforts of using supplementary cementitious materials or finding alternatives to Portland cement are necessary. The introduction of “geo-polymers” as a novel binder promises to be a good prospect for introduction into the concrete industry as an alternative to Portland cement. Geo-polymer concrete is a ‘new’ material that does not use Portland cement as a binder. Instead, a source of material such as fly ash, that is rich in Silicon (Si) and Aluminium (Al), is reacted by alkaline liquids to produce the binder [5]. Considerable researches have been conducted on geopolymer concrete [6]. However, very little is reported on the fiber reinforced geopolymeric composites [7-9]. And none of the above studies reported deflection hardening or strain hardening behaviour in bending or tension.

This paper reports the preliminary results on the development of geo-polymer based DFRCC where the cement based binder in DFRCC is replaced by fly ash based geo-polymer binder. The fly ash is activated by alkaline liquids (sodium hydroxide and sodium silicate). The newly developed geo-polymer based DFRCC is the first of its kind in the field of HPFRCC where Portland cement is completely replaced by class F fly ash.

2 EXPERIMENTAL PROGRAM

The experimental program is divided into two parts. In the first part, cement based DFRCC containing steel and PVA fibres are considered. The effects of sand sizes (maximum sand sizes of 0.6mm and 1.18mm) and sand/cement ratio (0.5 and 0.75) on the deflection hardening behaviour are also evaluated in the part. The total volume fraction of fibres is limited to 2% for all fibre types. The second part, where geo-polymer based DFRCC are considered, is similar to the first part in every aspect, except the matrix where cement is replaced by class F fly ash and is activated using alkaline activators (Sodium hydroxide and sodium silicate).

3 MATERIALS, MIXING, CURING AND MIX PROPORTIONS

The cement used in the study is general purpose (GP) Portland cement which corresponds to ASTM type I. The fly ash used is originated from Collie power station in Western Australia and satisfies ASTM class F classification. The fly ash consists of an amorphous part about 60% by wt. and a crystalline part about 40% by wt. [10]. The chemical composition of fly ash is shown in Table 1. The crystalline part of the fly ash has low reactivity and acts as fine aggregate in the binder system. The activating solutions used are sodium silicate with a chemical composition of (wt.%): Na_2O=14.7, SiO_2=29.4 and water=55.9. The other characteristics of the sodium silicate solution are specific gravity=1.53 g/cc and viscosity at 20^{O}C=400 cp. The sodium hydroxide solution is prepared from analytical grade sodium hydroxide pellets. The mass of the NaOH solids in the solution varied depending on the concentration of the solution expressed in terms of molar, M. In this study, the NaOH solution with a concentration of 8M is considered and consisted of 8X40=320gms of NaOH solids per liter of the solution, where 40 is the molecular weight of NaOH. The NaOH (Sodium Hydroxide) is first mixed with de-ionized water with the ratio of 0.32:1 and produce sodium hydroxide solution. During the mixing of sodium hydroxide solution, the white sodium hydroxide pellets were slowly dissolved by the addition of de-ionized water. A rise of temperature occurred as the sodium hydroxide pellet slowly dissolved into solutions. And then the sodium hydroxide solution is mixed with Na_2SiO_3 (Sodium Silicate) with the ratio of 0.4:1 and produced the alkali activator. The alkali activator solution is then used for the mixing of geo-polymer based cementitious composites.

The mixing is carried out in a Hobart Mixer. First sand and cement or fly ash (in case of geopolymer matrix) are dry mixed for approximately 2 minutes and then water or alkaline activator solution (in case of geopolymer matrix) is slowly added into the mix and continues to mix for another 3 minutes. The fibres are then slowly added to the wet mix and continued mixing until the fibres are well dispersed in the mix.

The geopolymer based DFRCC specimens undergone stream curing at 60°C immediately after casting, for 24 hours. The stream curing is carried out in the stream curing room in the laboratory. The specimens are then demolded after 24 hours and stored in the laboratory in open air until the date of testing. The specimens for cement based DFRCC are demolded after 24 hours and stored in the curing tanks where they are subjected to standard wet curing conditions. All specimens are tested after 28 days of casting.

Table 2 shows the mix proportions for cement based and geopolymer based DFRCC. Cement based DFRCC is considered in part A and geopolymer based DFRCC is in part B of this study. In each part, four series are considered where the effect of sand/binder ratios and sand sizes on the deflection hardening behaviour are evaluated. In each series, three types of micro fibres are considered, steel fibre and two types of PVA (Polyvinyl alcohol) fibres. The steel fibre is 10mm in length, whereas the PVA fibres are of two different lengths. One type of PVA fibre is 8mm long and termed as “PVA-1” and the other type is 12mm long and termed as “PVA-2”. Both are of different diameters, strengths and modulus. The properties of fibres are given in Table 3.

For each series, three prismatic specimens of 20X75X300 mm in dimension are cast. All specimens are tested in four-point bending using an Instron testing machine under displacement control with a loading rate of 0.5mm/min. A schematic of the bending test setup is shown in Fig. 1. The results shown in the figures are the average load-deflection responses of three specimens in each series and in each fiber type.

4. PARAMETERS DESCRIBING DEFLECTION HARDENING BEHAVIOUR OF DFRCC

A typical deflection hardening response of DFRCC is shown in Fig. 2. The DFRCC showing deflection hardening behaviour generates a higher load carrying capacity after the first cracking compared to deflection softening fiber reinforced composites. In this research the first cracking point is considered as the point where nonlinearity in the load-deflection curve becomes evident. This point is termed as limit of proportionality (LOP) according to the ASTM C1018-97 [11]. Researchers have noticed difficulty [12] of correctly identifying first crack (peak) strength of deflection hardening fiber reinforced cement composites as required by the new version of ASTM C 1609/C 1609M-07 [13]. The load value at LOP is termed as

P_{LOP} and the corresponding deflection value is δ_{LOP} in Fig. 2. The stress obtained when the first crack load is inserted into equation (1) below is defined as the first crack strength, f_{LOP}. The modulus of rupture (MOR) also known as ultimate flexural strength is defined as the point where softening start after the LOP in the load-defelction curve in Fig. 2.

$$f_{LOP} = P_{LOP} \frac{L}{bh^2} \qquad \text{(Eqn. 1)}$$

Where, L=span length, b=width of the specimen and h=height of the specimen.

4 RESULTS AND DISCUSSIONS:

4.1 Deflection hardening behaviour of geopolymer based DFRCC

Figures 2-5 show the deflection hardening behaviour of both cement based and geopolymer based DFRCC and the comparison between the two types of binder can be seen in the same figures. Generally, the composite containing 2% steel fibre exhibited much higher modulus of rupture (MOR) that those containing PVA-1 and PVA-2 fibres of the same volume fraction irrespective of matrix types, sand contents and sand sizes. But its deflection capacity (deflection at peak load) is much lower than that containing PVA-2 fibre. However, its deflection capacity is comparable to that containing PVA-1 fibre. The higher MOR and the smaller deflection capacity of steel fibre reinforced DFRCC compared to its counter parts PVA fibres system is due to the high modulus of steel fibres. The lower MOR with considerable higher deflection capacity of PVA fibre reinforced composites is due to the low modulus of PVA fibres. Other researchers also observed similar behaviour in both steel and PVA fibre reinforced cement based composites [4]. The geopolymer based DFRCC exhibits comparable deflection hardening and multiple cracking behaviour to the cement based system with only exception with the composite containing PVA-2 fibre, where no deflection hardening behaviour is noticed. It could be due to rupturing of PVA-2 fibers and can be attributed to the high fibre/matrix bond and the low tensile strength of PVA-2 fibre. Previous research suggests that, in addition to friction bond, chemical bond also develops between PVA fibre and cement matrix [14]. The frictional bond between geopolymer matrix and PVA-2 fiber and the fracture toughness of geopolymer matrix could also be the factors for inferior performance observed in PVA-2 fiber reinforced geopolymer composites. If we compare the deflection hardening behaviour of cement and geopolymer based DFRCCs containing PVA-1 and PVA-2 fibers, it can be seen that the deflection hardening is achieved in geopolymer based DFRCC containing PVA-1 fibers. Therefore, the high fracture toughness cannot be blamed in the former case where deflection hardening is achieved in geopolymer based DFRCCs containing PVA-1. Thus it is apparent that the interfacial bond between PVA-2 and geopolymer matrix might responsible in this case in addition to the low tensile strength of PVA-2 fiber. More research on the behaviour of fracture toughness of geopolymer matrix and its bond strength with PVA-2 fiber and need to be thoroughly investigated in order to obtain an insight into the observed behaviour.

4.2 *Effect of sand/binder ratio on the deflection hardening behaviour:*

The effects of sand/binder ratio on the deflection hardening behaviour of geopolymer based and cement based DFRCC are shown in Figs. 7-10. It can be seen that, by lowering the sand content (S/B=0.5), the improvement in the deflection hardening behaviour of cement based DFRCC can be achieved irrespective of sand sizes (see Figs. 7-8). The first crack strength (f_{LOP}) is found to be mostly unaffected in the cement based DFRCC by lowering the sand content. However, the modulus of rupture **(MOR)** is increased by lowering the sand contents in the cement based DFRCC. And by increasing the gap between the f_{LOP} and MOR (as shown in Fig. 6) the deflection hardening behaviour can be ensured. It can also be seen that the deflection at first crack is not affected due to lowering the sand content. However, the deflection at peak load ($\delta_{\text{peak load}}$ in Figs. 7-8) is increase in those composites by lowering the sand content, which clearly indicates high ductility in those composites. In the case of geopolymer based DFRCC similar results are observed except the composite containing PVA-2 fiber. It is observed that, by reducing the amount of sand, the f_{LOP} is decreased in the geopolymer based DFRCC composites containing maximum sand size of 0.6mm (see Fig. 9). However, no such reduction in f_{LOP} is observed when bigger size sand is used in the geopolymer based DFRCC. This could be due to the fact that the matrix becomes tougher by incorporating the bigger size sand [15]. With regard to the MOR values of geopolymer based DFRCC, the reduction of sand content in the DFRCC containing bigger size sand exhibited increase in the MOR. The geopolymer composite containing finer sand, however, does not exhibit such improvement.

4.3 *Effect of sand sizes on the deflection hardening behaviour:*

The effect of sand sizes on the deflection hardening behaviour of geopolymer based and cement based DFRCC is shown in Figs. 11-14. In case of cement based system, the deflection hardening behaviour is affected by increasing the sand size, which is due to increase in the LOP values. The MOR is also increased due to increase in the maximum size of sand from 0.6mm to 1.18mm. In all cement based DFRCC the f_{LOP} is less than MOR which clearly indicates their deflection hardening irrespective of fiber types. In the case of geopolymer based system a slightly different scenario is observed. The f_{LOP} is decreased by using finer sand and by lowering the sand content in the geopolymer based system. The MOR values are also increased by increasing the sand content in the composite containing maximum sand size of 0.6mm. However, no such improvement is noticed when the sand content is reduced. The geopolymer based DFRCC containing PVA-2 fiber did not exhibited deflection hardening behaviour, which is due to relatively lower MOR than that of cement based system. It should be noted that the modulus of elasticity and tensile strength of PVA-2 fiber are lower than that of PVA-1 and the low MOR of DFRCC containing PVA-2 is due to its low modulus and fiber strength.

Matrix toughness plays an important role in the deflection hardening behaviour of DFRCC. Matrix with low toughness is desirable as it exhibits low first crack strength of the composite and by increasing the gap between the first crack strength and the ultimate strength the deflection hardening can be promoted. The first crack strength (the end point of the linear portion of the load-deflection curve considered in this study) of geopolymer based DFRCC are found lower than or at least similar to that of cement based system irrespective of sand sizes and contents. However, this needs to be confirmed through determination of the fracture toughness of geopolymer matrix and its first crack strength.

5 CONCLUSIONS:

Within the limited fibre types, sand contents and sand sizes used in this study, the following conclusions are made:

- Deflection hardening behaviour is achieved in the geopolymer based DFRCC containing 2% steel fibre by volume.
- Deflection hardening behaviour is also achieved in the geopolymer based DFRCC containing 2% PVA-1 fibre by volume.
- Deflection hardening behaviour is not observed in the geopolymer based DFRCC containing PVA-2 fibre by volume. This could be due to high bond of fibre/matrix interface and the low strength of PVA-2 fibre.

- The increase in sand content and sand size adversely affected the deflection hardening behaviour of cement based DFRCC.
- An opposite trend is observed in case of geopolymer based DFRCC containing steel and PVA-1 fibers, where deflection hardening behaviour is improved by increasing the sand size and sand content.

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Table 1. Chemical compositions of fly ash

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI
51.5%	23.63%	15.3%	1.74%	1.2%	0.28%	0.38%	0.84%	1.78%

Table 2. Experimental program and mix proportions

	Series no.	Fibre types (by volume): Steel	Fibre types (by volume): PVA (L=8 mm)	Fibre types (by volume): PVA (L=12 mm)	Mix proportions by wt.: Cement	Class F fly ash	Sand/Binder: d_{max} = 1.18mm	Sand/Binder: d_{max} = 0.6mm	Water/ cement	Alkali activator/ fly ash: NaOH (8M)	Alkali activator/ fly ash: Na_2SiO_3
Cement based DFRCC – **Part A**	1	2%									
			2%		1	-	0.75	-	0.45	-	-
				2%							
	2	2%									
			2%		1	-	0.5	-	0.45	-	-
				2%							
	3	2%									
			2%		1	-	-	0.75	0.45	-	-
				2%							
	4	2%									
			2%		1	-	-	0.5	0.45	-	-
				2%							
Geo-polymer based DFRCC – **Part B**	5	2%									
			2%		-	1	0.75	-	-	0.13	0.32
				2%							
	6	2%									
			2%		-	1	0.5	-	-	0.13	0.32
				2%							
	6	2%									
			2%		-	1	-	0.75	-	0.13	0.32
				2%							
	8	2%									
			2%		-	1	-	0.5	-	0.13	0.32
				2%							

Note: Binder = Cement or fly ash

Table 3. Properties of fibre

Types of Fibre	Length (mm)	Diameter (mm)	Modulus of elasticity (MPa)	Fibre Strength (MPa)	Density (gm/cm^3)	Elongation (%)
PVA-1	8	0.04	40,000	1,600	1.3	6
PVA-2	12	0.10	25,000	1,100	1.3	10
Steel	10	0.12	200,000	2,500	7.8	-

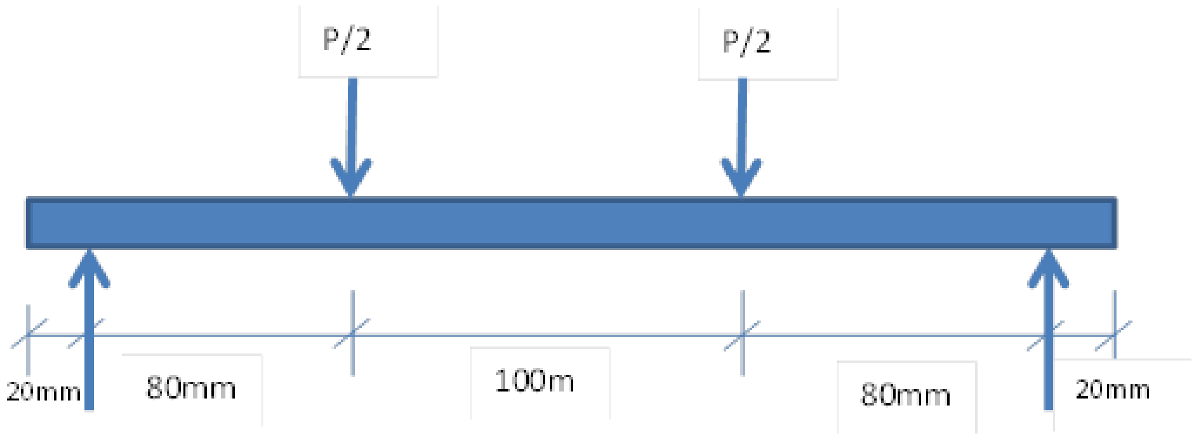

Figure 1. Bending test setup

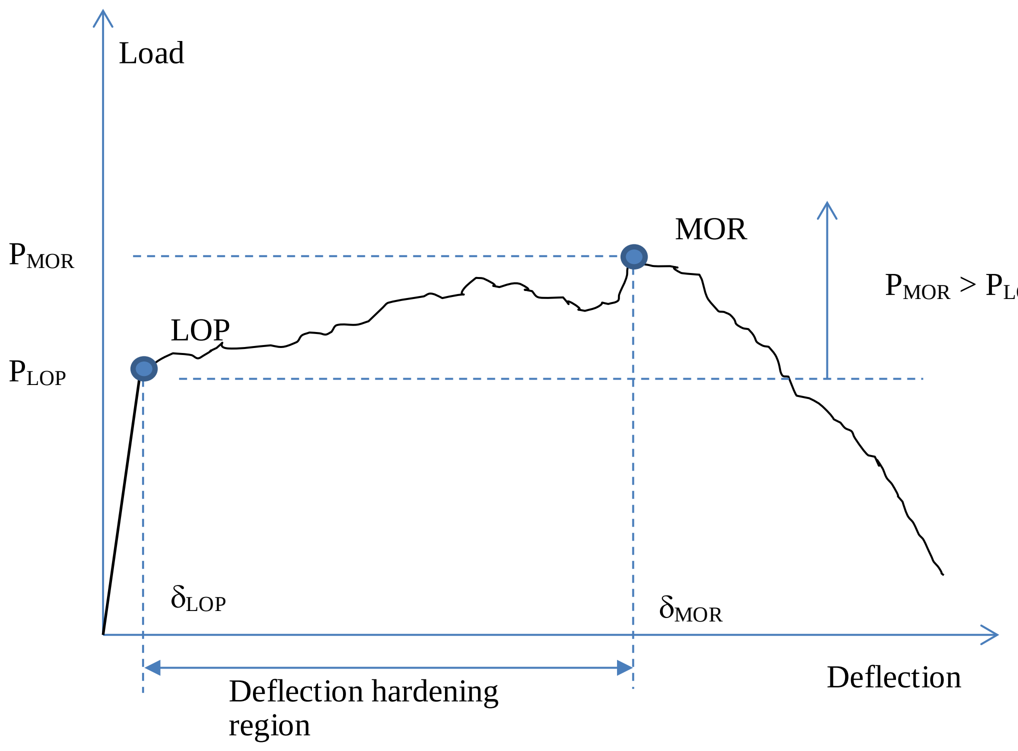

Figure 2. Typical deflection hardening behaviour of DFRCC.

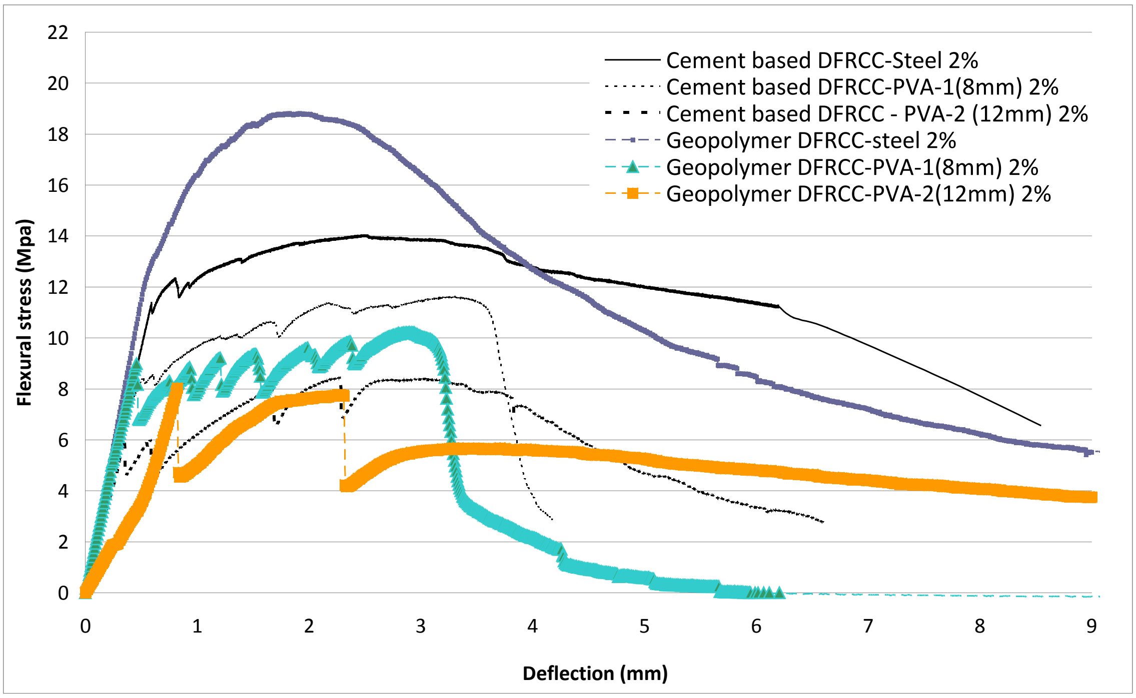

Figure 3. Comparison of deflection hardening behaviour of cement based and geo-polymer based DFRCC containing sand/binder=0.75 and max sand size of 0.6mm.

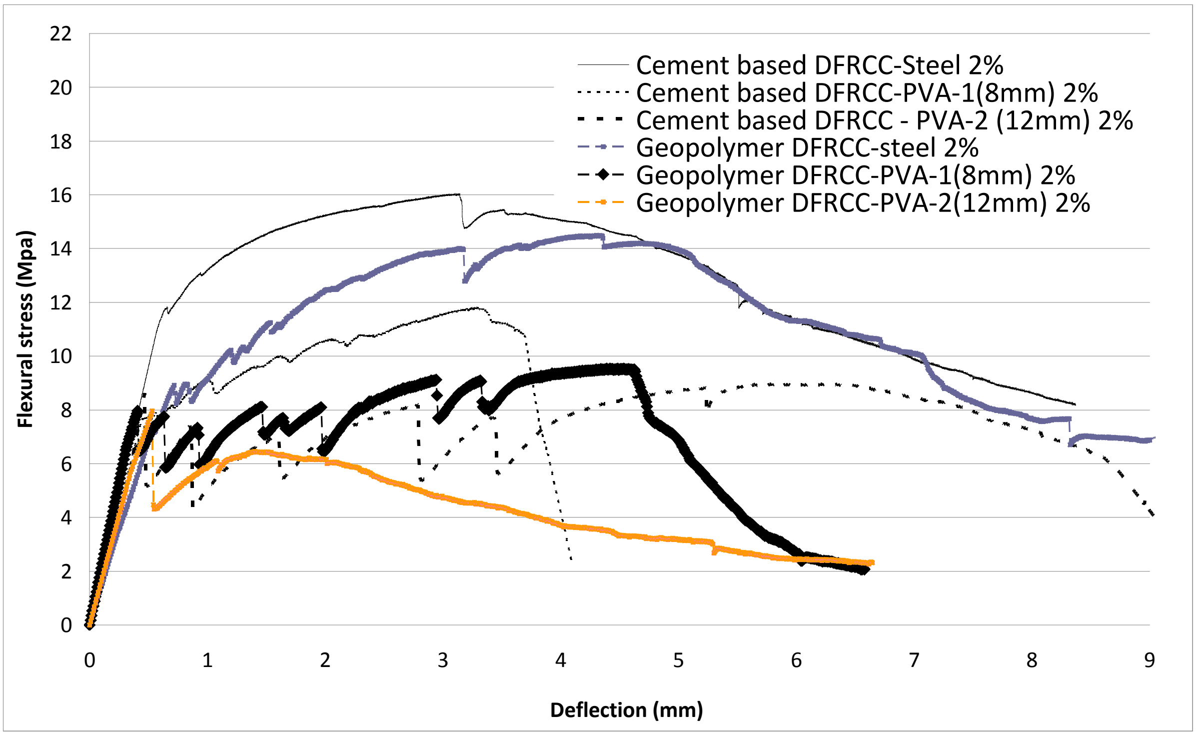

Figure 4. Comparison of deflection hardening behaviour of cement based and geo-polymer based DFRCC containing sand/binder=0.5 and max sand size of 0.6mm.

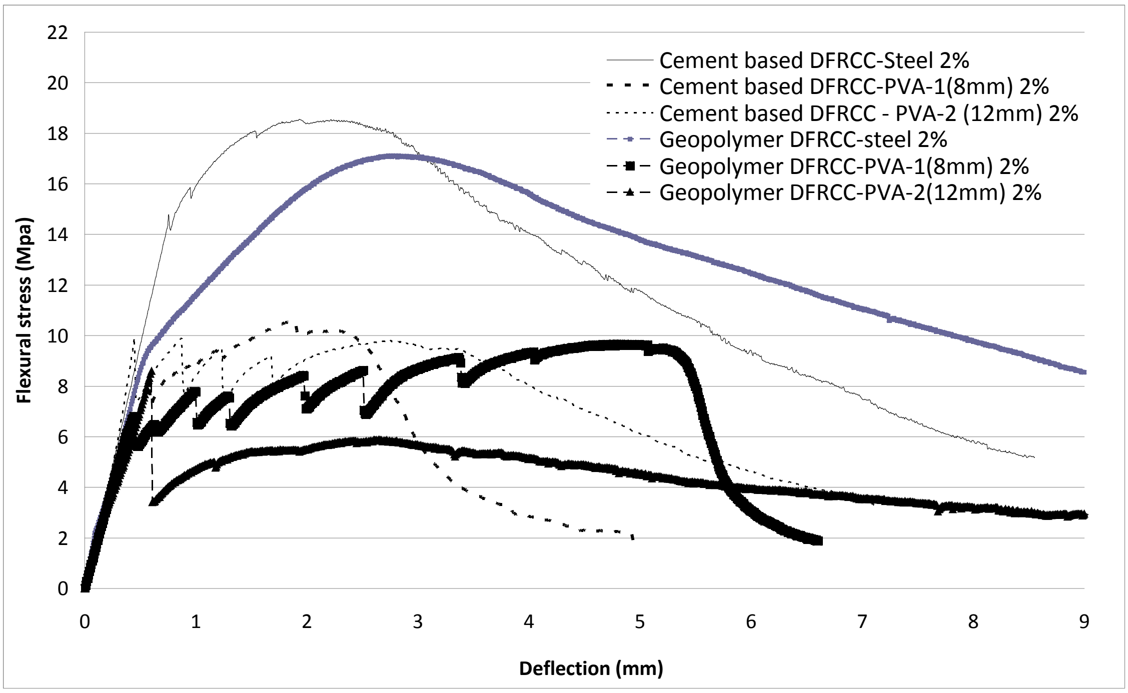

Figure 5. Comparison of deflection hardening behaviour of cement based and geo-polymer based DFRCC containing sand/binder=0.75 and max sand size of 1.18mm.

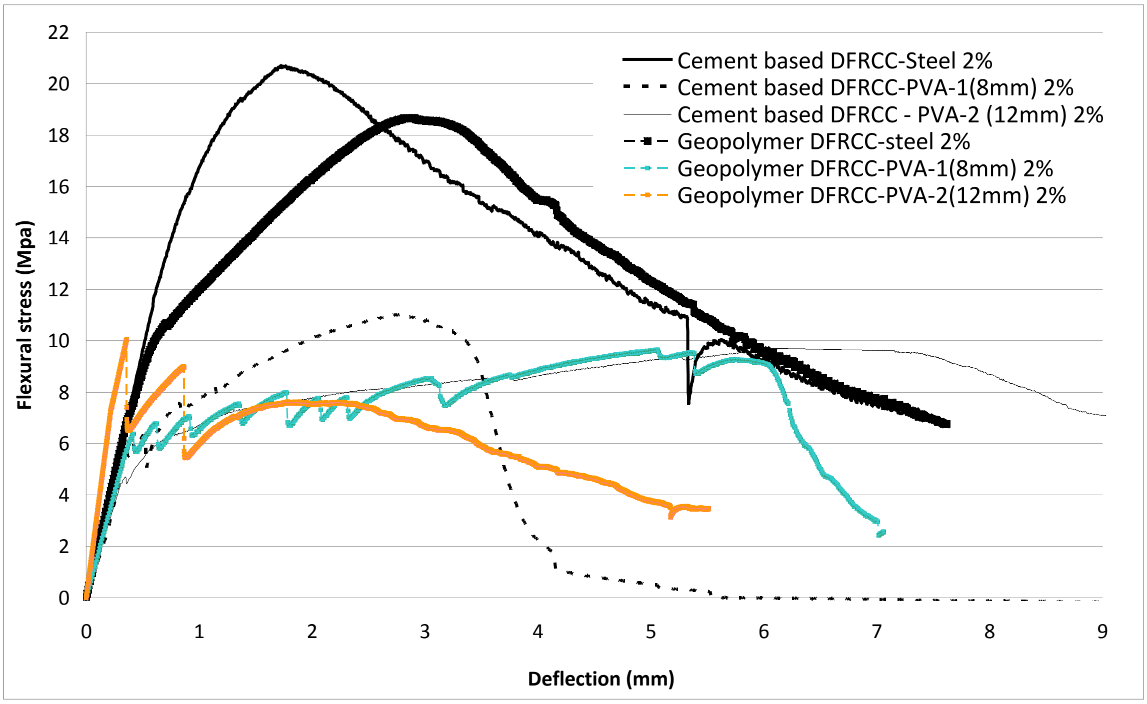

Figure 6. Comparison of deflection hardening behaviour of cement based and geo-polymer based DFRCC containing sand/binder=0.5 and max sand size of 1.18mm.

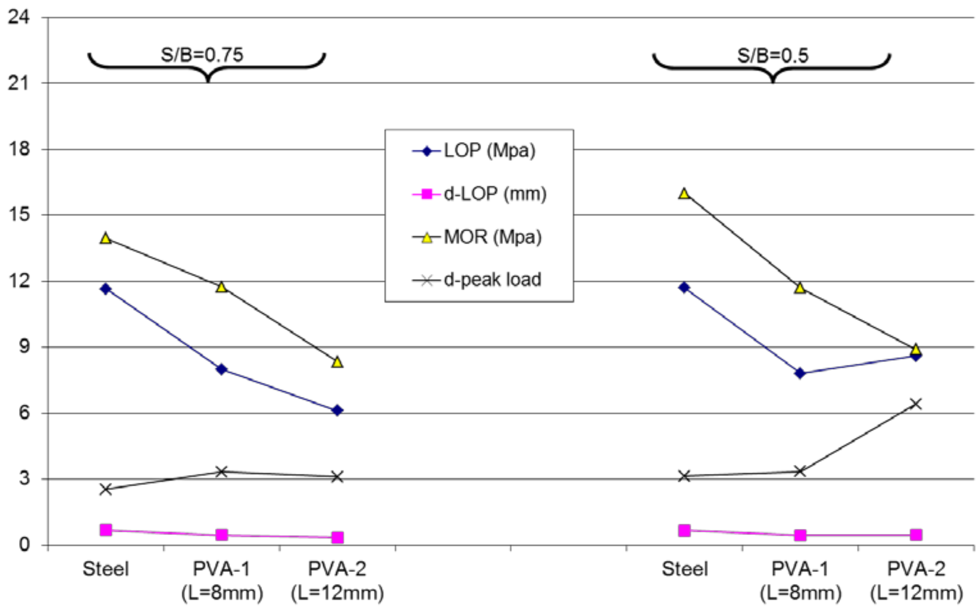

Figure 7. Effect of sand/binder (S/B) ratios on the deflection hardening behaviour of cement based DFRCC containing max sand size of 0.6mm.

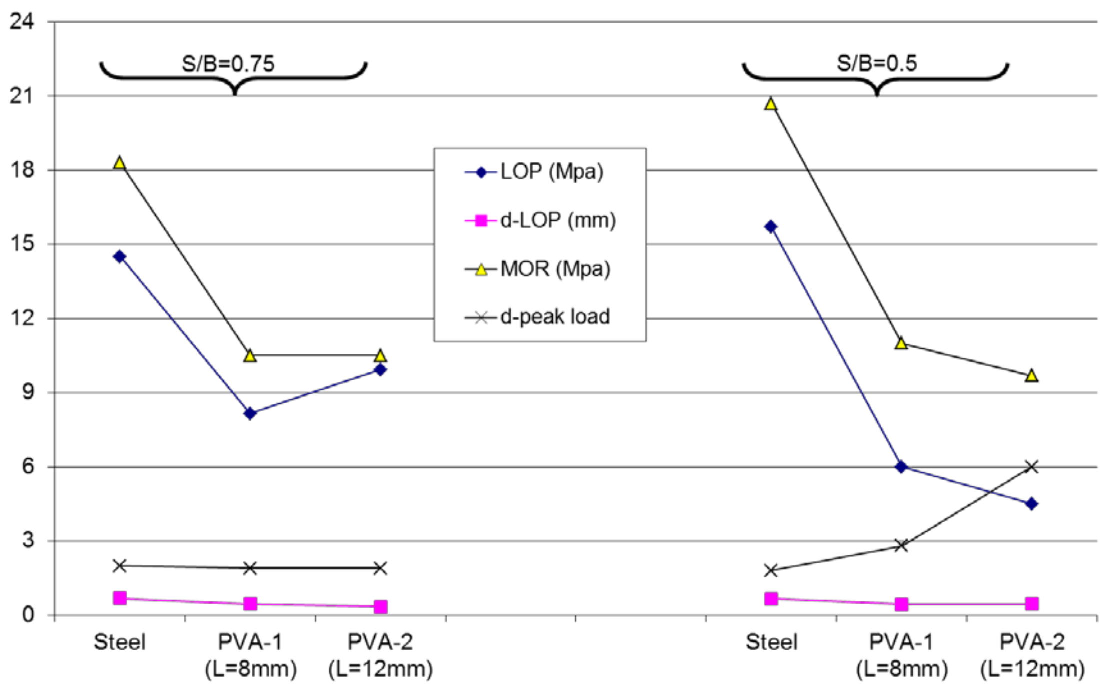

Figure 8. Effect of sand/binder (S/B) ratios on the deflection hardening behaviour of cement based DFRCC containing max sand size of 1.18mm.

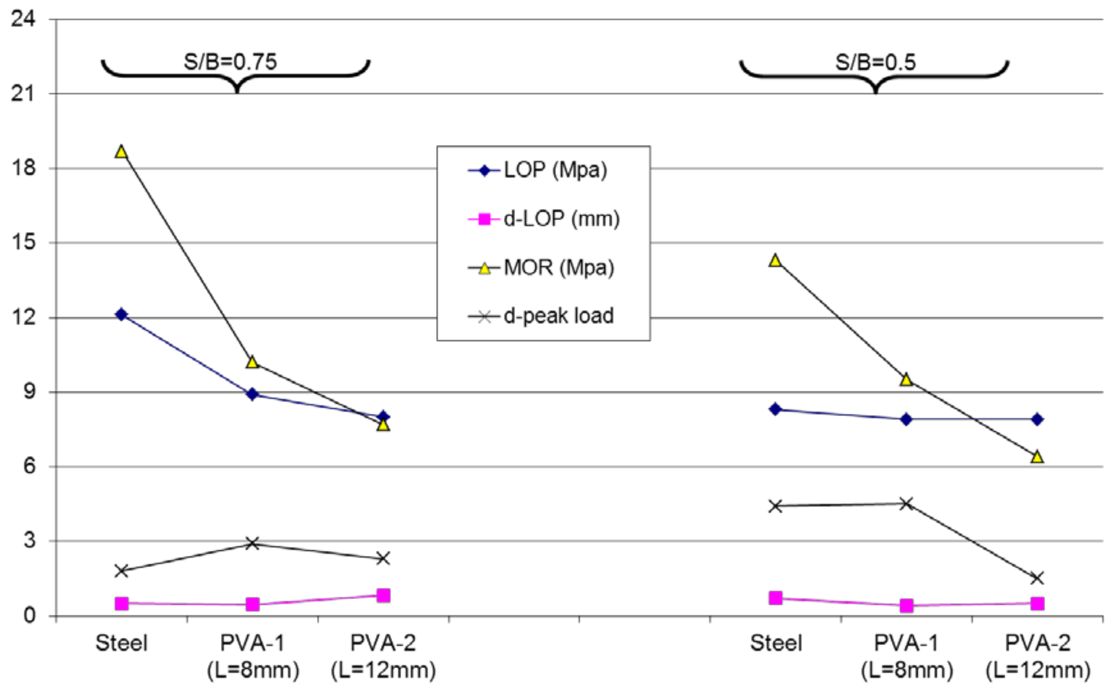

Figure 9. Effect of sand/binder (S/B) ratios on the deflection hardening behaviour of geopolymer based DFRCC containing max sand size of 0.6mm.

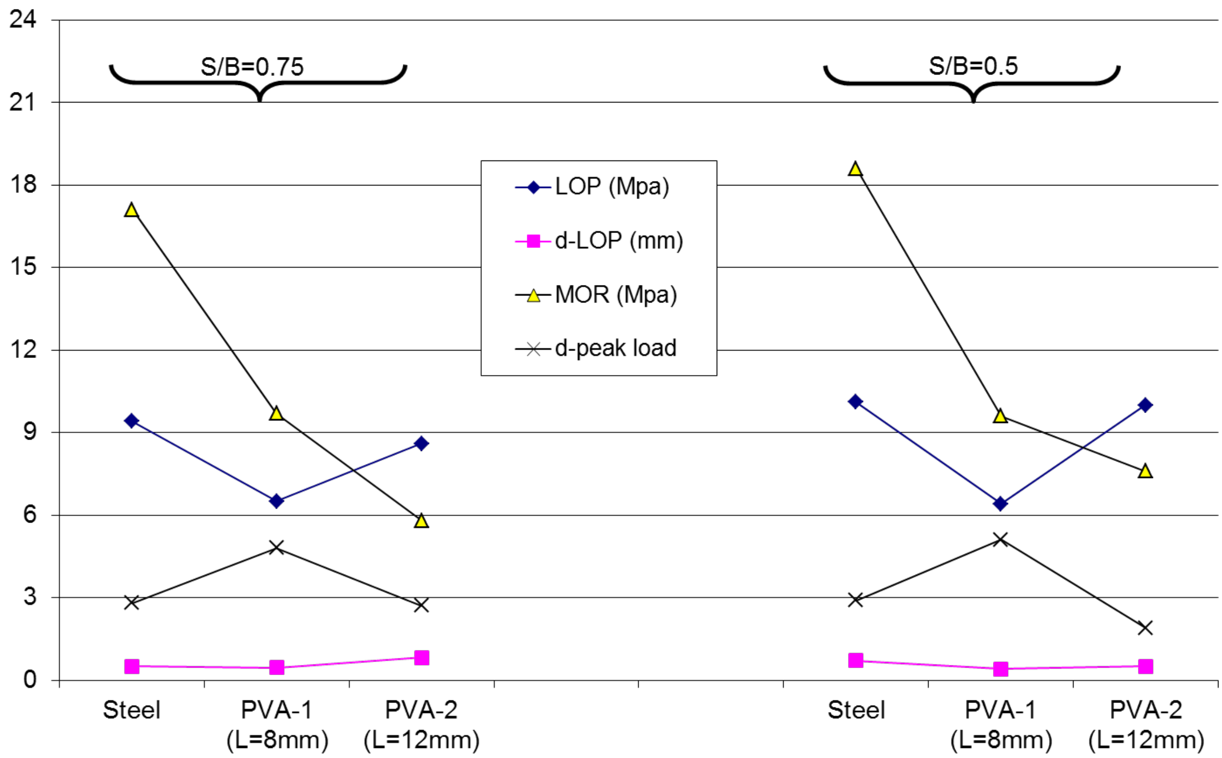

Figure 10. Effect of sand/binder (S/B) ratios on the deflection hardening behaviour of geopolymer based DFRCC containing max sand size of 1.18mm.

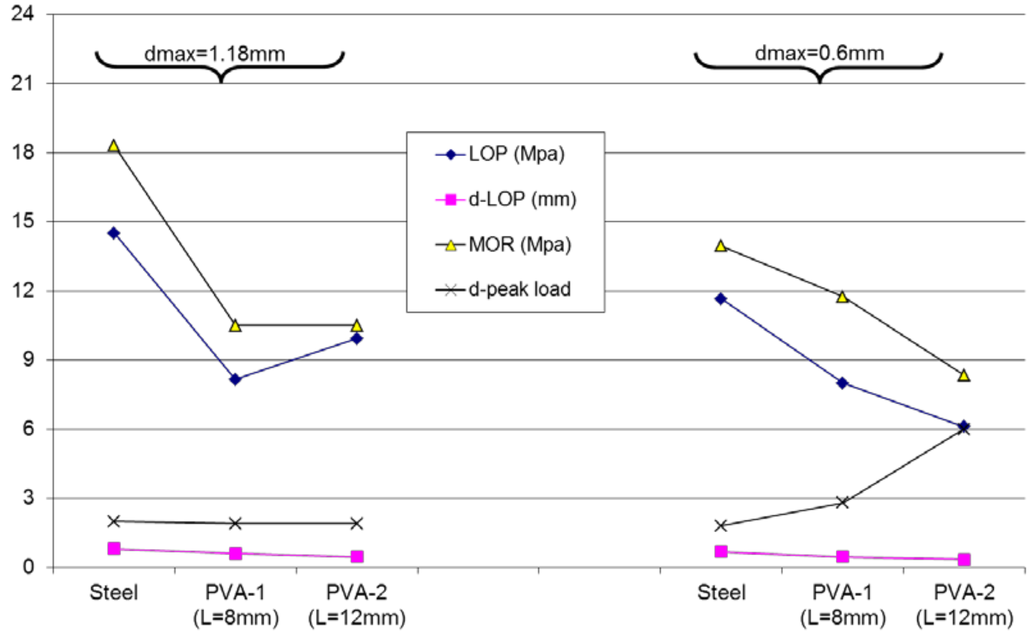

Figure 11. Effect of sand size on the deflection hardening behaviour of cement based DFRCC containing S/B=0.75.

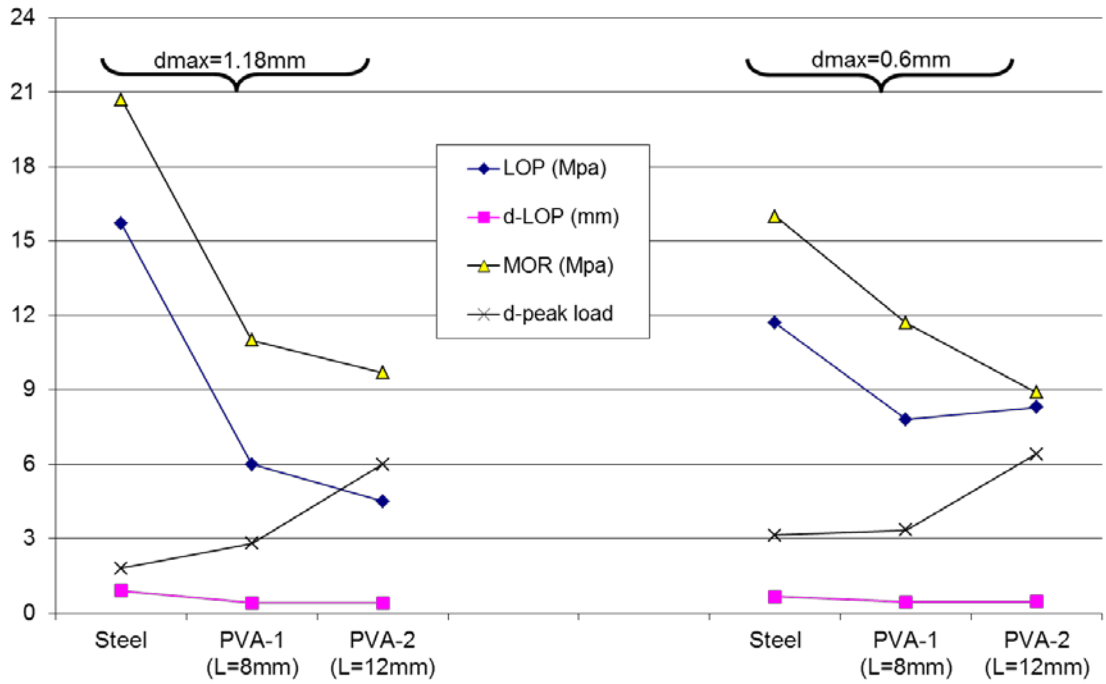

Figure 12. Effect of sand size on the deflection hardening behaviour of cement based DFRCC containing S/B=0.5.

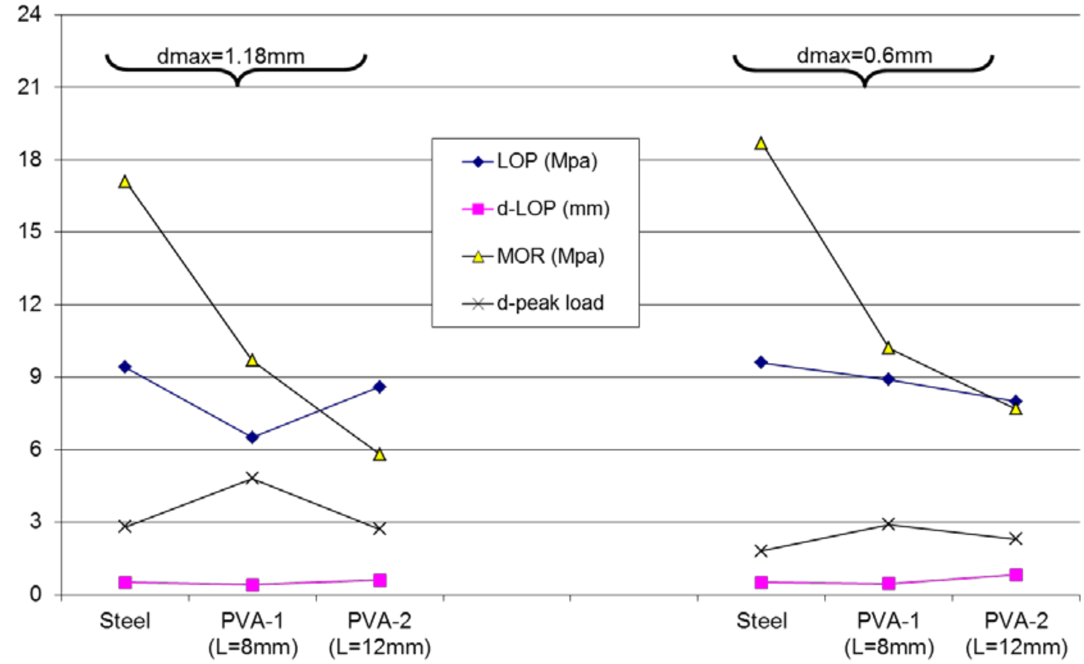

Figure 13. Effect of sand size on the deflection hardening behaviour of geopolymer based DFRCC containing S/B=0.75.

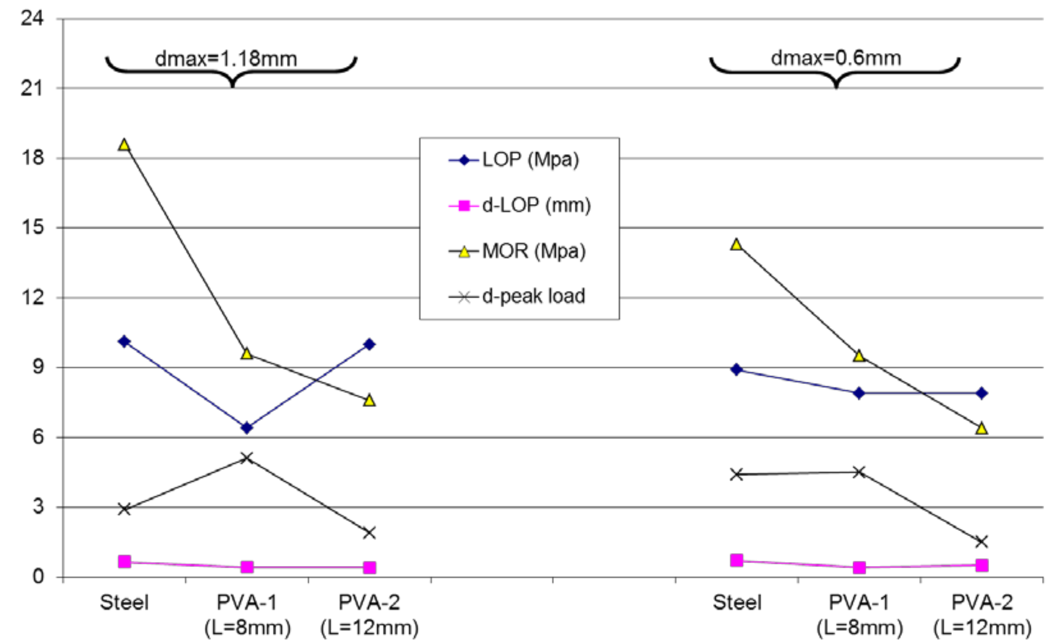

Figure 14. Effect of sand size on the deflection hardening behaviour of geopolymer based DFRCC containing S/B=0.5.